Journal of Coastal Conservation 6: 5-14, 2000
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Impact of continental margins in the Mediterranean Sea: Hints from the surface colour and temperature historical record

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Abstract. The surface colour and temperature fields of the Mediterranean Sea, as appearing in time series of basin-wide images available in the CZCS (1979-1985) and AVHRR (1982-1991) historical archives, differentiate between basin interior and continental margins affected by coastal patterns, river plumes, and mesoscale features. The original data were processed to apply calibration factors, to correct for atmospheric contamination, and to estimate chlorophyll-like pigment concentration and surface temperature. Composites were derived, as monthly and annual means, using a fixed equal-area projection with a 1-km^2 pixel grid. Enhanced pigment values and lower temperatures along the northern coastal areas (i.e. the Ligurian, Provençal and Balearic basins, as well as the Adriatic and Aegean Seas) have been associated with the impact of runoff from continental margins (i.e. both a direct impact due to the sediment load and one induced on the planktonic flora by the associated nutrient load) and with vertical mixing due to the prevailing winds (i.e. the Mistral in the northwest, the Bora in the Adriatic, the Etesians in the Aegean). The pattern of increasing pigments and decreasing temperatures is seen to develop in the monthly images from the coastal zone towards the open sea from summer to winter, and then back from winter to summer. The southern coastal areas show different values, namely lower pigments and higher temperatures (except in areas where the data are altered by signal contamination). It is suggested that differences in geomorphology and meteorology of the basin margins have an impact on both water biogeochemistry and dynamics, influencing the bio-optical and thermal properties of the various sub-basins, and of the entire Mediterranean region.

Keywords: Biogeographical province; Sea surface colour; Sea surface temperature; Seasonal trend.

Introduction

The compilation of historical time series of remote sensing data, collected primarily in the visible and infrared spectral ranges, has for the first time pointed out a marked space/time heterogeneity of a number of surface parameters for the Mediterranean Sea, derived from optical and thermal indices (Barale & Zibordi 1994; Santoleri et al. 1994). The variability observed in the satellite data record points at specific biogeographical provinces, in particular those situated along coastal margins, where a significant relationship seems to exists between such indices and the climatic features of the region.

Sea surface colour and temperature images give complementary views of the semi-enclosed water bodies in the Mediterranean Sea (Barale & Filippi 1997). The space and time gradients observed in the surface colour and temperature fields of the Mediterranean Sea differentiate between basin interior and continental margins affected by persistent mesoscale dynamic features (e.g. gyres and coastal filaments anchored to geographical features), river plumes (e.g. those of the Ebro, Po, Rhône, Nile), and extensive coastal patterns.

In the following, an analysis of long-term statistics of the optical and thermal fields, derived from the existing Coastal Zone Colour Scanner (CZCS) and Advanced Very High Resolution Radiometer (AVHRR) time series, will be reported. The historical data have been used to explore the role played by geographical setting and atmospheric forcing in establishing the observed space/time distribution of water parameters. The impact of continental influence through river and coastal runoff, and that of wind-driven upwelling and coastal mixing will be addressed, leading to the hypothesis that exchanges between coastal zones and open sea may have a major influence on the biogeochemical cycles of the entire Mediterranean basin.

The surface colour and temperature historical record

In order to highlight the impact of near-coastal features in the Mediterranean, time series of basin-wide surface colour and temperature images were developed, based on the historical CZCS (1979-1985) and AVHRR (1982-1991) archives.

The CZCS data set originates from the activities of the Ocean Colour European Archive Network (OCEAN) project, established in 1990 as a co-operation between the Joint Research Centre of the European Commission and the European Space Agency. The aim of the project was to generate a data base of CZCS data for the European enclosed and marginal seas, and to set up the scientific tools needed for its exploitation (Barale & Schlittenhardt 1994). In its five years of activity, the OCEAN Project has processed about 15 000 original (top-of-the atmosphere radiance) CZCS images, produced 7000 images showing surface reflectance and derived geophysical parameters, namely chlorophyll-like pigment concentration, and derived 3500 remapped, composite statistical images of the major European basins. In all, the Project has distributed thousands of data products and dedicated software to more than 40 user groups in Europe, as part of its Application Demonstration Programme.

The AVHRR data set originates from the activities of the Cloud and Ocean Remote Sensing around Africa (CORSA) project, conducted by the Joint Research Centre of the European Commission. The project aims at providing a quality controlled time series of surface, atmospheric and cloud parameters over a period of several years, at a resolution not available from other sources (a provisional description of the data set can be found in Nykjær 1995). The project has currently derived average SST maps, at weekly and monthly intervals, for the period from August 1981 to December 1991. It is intended to extend this time period, and to also derive cloud classification products. The data are

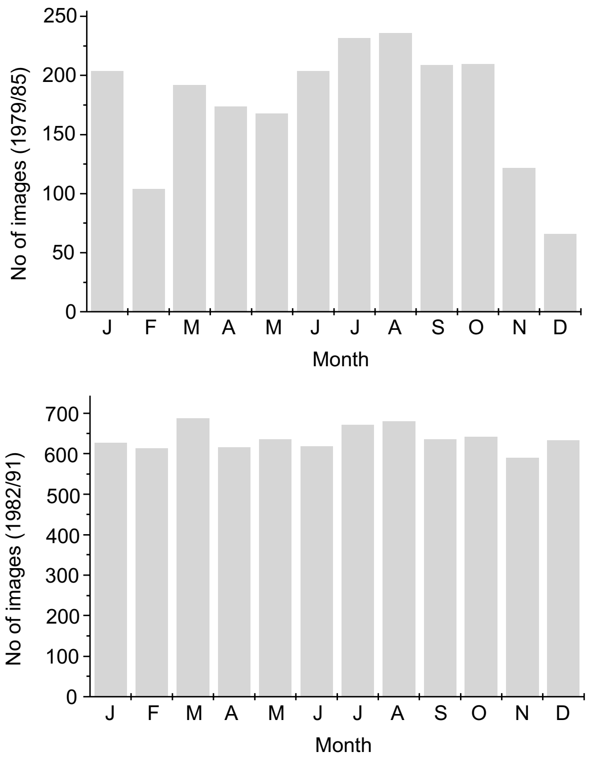

Fig. 1. Monthly breakdown of the number of CZCS (1979-1985) images, upper plate, and AVHRR (1982-1991) images, lower plate, used for the long-term composites.

derived by analysis of AVHRR data products. Currently 13 000 of these products have been processed and made available.

The raw data, after the masking of land pixels, were processed to apply sensor calibration algorithms, correct for atmospheric contamination, and derive chlorophyll-like pigment concentration and surface temperature values. Algorithms and models used to generate the OCEAN and CORSA data sets are described in Barale et al. (1993), Sturm (1993) and Nykjær (1995). Individual images were generated for each available non-cloudy day, co-registered using the same geographic equal-area projection and resolution (covering the whole Mediterranean basin, but excluding the Black Sea), and then averaged pixel by pixel, to compute multi-annual composites on a yearly and monthly basis. Each composite covers an area of 4000 $\times$ 2000 km, with a 1-km pixel size. The yearly composites of pigment concentration and surface temperature were derived respectively from 2465 CZCS original images and from 9396 AVHRR original images. The monthly breakdown of these totals is shown in Fig. 1. The statistical results obtained should be considered with caution, due to the CZCS and AVHRR limitations in retrieving quantitative parameters. However, an analysis of recurrent patterns was derived from the long-term composites (see Figs. 2 and 3), showing the average conditions of the Mediterranean surface pigment and temperature fields.

Given the pixel by pixel correspondence of the composites, multi-band annual and monthly images could be constructed, in which the surface pigment and temperature histogram-matched data constituted two different bands. An unsupervised classification of the annual two-band image was performed, to highlight the patterns inherent in the data, and chose the best suited number and boundaries of classes (Fig. 2). The unsupervised classification is based on the Iterative Self-Organising Data Technique (ISODATA) clustering, a method that uses minimum spectral distance to cluster pixels with similar spectral characteristics (Tou & Gonzales 1974). The algorithm requires that maximum number of clusters, convergence threshold, and number of iterations be specified, and defines initial classes evenly distributed in data space. Then, all pixels are clustered using minimum distance criteria. At the following iteration, new means are computed for each cluster, and used for defining classes in the next step. The process continues until the percentage of pixels classified reaches the convergence threshold, or the maximum number of iterations is done. In the present case, the initial classification of the annual pigment-temperature image was done using eight clusters, a 95% convergence threshold, and a maximum of five iterations.

a

b

c

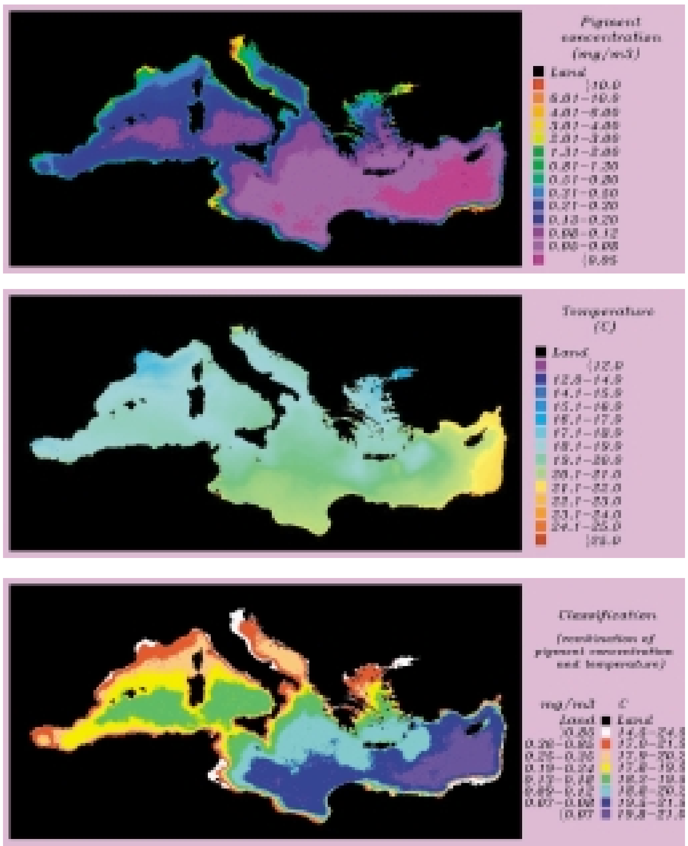

Fig. 2. a. Annual means of chlorophyll-like pigment concentration derived from the CZCS (1979-1985) data set; the colour coding represents mg/m^3. **b.** Sea surface temperature derived from the AVHRR (1982-1991) data set; the colour coding represents °C. **c.** Unsupervised classification of the Mediterranean Sea characteristics derived from a combination of the annual pigment and temperature images; the arbitrary colour coding highlights the eight different classes adopted.

A supervised classification based on the same minimum spectral distance technique was used to classify the monthly pigment-temperature images (Fig. 3). As this method requires pre-defined classes, the clusters obtained from annual image classification were used as Regions of Interest (ROI). Then, all pixels in the monthly images were assigned to the closest ROI.

Near-coastal and basin-wide space/time features

Both the CZCS and the AVHRR mean annual composites (see Fig. 2) show marked differences between western and eastern sub-basins, inshore and offshore domains, as well as northern and southern near-coastal areas.

The mean annual pigment concentrations and surface temperatures show that the transition between the western and the eastern regime corresponds with the line of narrow straits going from the Sicily Channel, to the Strait of Messina and the Strait of Otranto. In the annual means, the western basin is characterized by higher pigment concentrations and lower temperatures than the eastern basin (where the Aegean Sea represents a notable exception). Contrary to geographic subdivisions commonly used, this qualifies the Adriatic Sea – and the northern Aegean, up to a point – as one of the western sub-basins, at least as far as the pigment and temperature fields are concerned.

The spatial gradients in the surface colour image differentiate between the areas of high pigment concentration along the basin margins and the mainly oligotrophic basin interior. The inshore, coastal domain is influenced by persistent mesoscale dynamics (i.e. gyres and coastal filaments anchored to geographical structures), by river plumes, and by extensive coastal runoff patterns. The main permanent features of the Mediterranean, appearing in both the pigment and temperature fields, include the Alboran double gyre system (the western being more pronounced in the pigment field, while the eastern is more evident in the temperature one), the giant filament of Capo Passero, at the southern tip of Sicily, as well as the (cyclonic) cores of the Western Cretean gyre and Rodhes gyre. In addition, all of the main rivers entering the Mediterranean Sea, i.e. the Ebro, Rhône, Po and Nile, form distinct permanent plumes (Barale & Larkin 1998). The surface temperature gradients, instead, point to a smoother transition between the inshore and the offshore domain, but present also peculiar dynamic features along the basin margins, particularly in the northwestern basin.

The data show similarities in the pigment and temperature near-coastal dynamics of the Ligurian, Provençal and Balearic basins and the Adriatic Sea. Even the northern Aegean Sea coast has characteristics similar to those of the northwestern basins. The northern Mediterranean coastal arc is characterized by important orography, with a wet climate for at least part of the year, and rivers draining large watersheds. Moreover, major winds are responsible for deep water formation at various near-coastal sites in the same area (i.e. the Mistral in the northwestern Mediterranean, the Bora in the northern Adriatic, the Etesians in the Aegean). This suggests that the rim of higher pigments and lower temperatures around the northern part of the Mediterranean might be associated with the impact of runoff from continental margins (i.e. both a direct impact due to the sediment load and one induced on the planktonic flora by the associated nutrient load), and with vertical mixing processes, still along coastal margins, due to the prevailing winds.

The southern coastal areas have clearly different characteristics, namely lower pigment values and higher temperatures – except in areas where the data are somewhat altered by signal contamination. All along the African coastal zone, in the eastern basin, pigment concentrations are higher than expected due to signal contamination caused by the notorious CZCS sensor ringing problem in the downscan direction. Further, the apparently enhanced pigments on the shallow banks off southern Tunisia are due to other factors than runoff and/or mixing. In fact, much of the apparent high concentration is due to direct bottom reflection in an area of shallow clear waters (i.e. around Kerkenna Island). The shallow Tunisian banks have also a distinct signature in the surface temperature record, at least in fall and winter – when cooling in the shallow coastal basin is suspected to be a (minor) source of dense water.

The classification of Mediterranean waters (see Figs. 2 and 3c), performed on the basis of their mean annual colour and temperature, confirms the peculiarities of the 'northern' coastal zone, from the Alboran Sea, to the Ligurian/ Provençal basin, the Adriatic and the Aegean. The areas influenced by mixing processes – due to the main northerly winds or the large-scale gyres – are particularly evident in the classification of the annual images (note how the upwelling areas of western and southern Sardinia, as well as that of southwestern Sicily, also linked to Mistral outbreaks, are classified in the same way by the clustering algorithm). Dynamical features such as the incoming Atlantic jet (Taupier-Letage & Millot 1988), the northward current of Ionian waters entering the Adriatic on the eastern side of the Otranto Strait (Barale et al. 1986), the string of mesoscale gyres, the Western Cretean gyre and the Rodhes gyres in particular, appear as having distinct properties. The oligotrophic areas are also highlighted, in the western basin (e.g. the Thyrrenian Sea) and in the eastern basin (e.g. the Ionian Sea).

The main sub-basins present a distinct seasonality, superimposed to that of the Mediterranean as a whole. The general characteristics of the pigment and temperature fields are rather constant, while differences occur in the details composing the larger picture (Fig. 3). Seasonal variations are more pronounced in the western than in the eastern basin, with lower temperatures and higher concentrations in late winter and early spring (see the Plates for the Mediterranean, the western basin, and the eastern basin in Fig. 4). This points to a (biogeochemical) behaviour of the Mediterranean similar to that of a 'tropical' sea, where light is never a limiting factor, but nutrients always are (Yoder et al. 1993). In such a scenario, the surface pigment maximum would occur in the cold season, when the rains come to the Mediterranean region, coupled to maximum runoff, surface cooling and vertical mixing – as opposed to a minimum in the warm, dry season, when the water column is strongly stratified and no nutrient supply (from coastal zones or deeper layers) is readily available.

While most of the sub-basins seem to follow this general model, or possibly a combination of different features (see the Thyrrenian Sea Plate in Fig. 4), specific areas present quite different characteristics. Notably, in the western Mediterranean, the Ligurian-Provencal basin has a seasonality closer to that of a 'temperate' basin, with a pronounced spring bloom followed by a summer relative minimum, and a secondary (large, and not fully understood) peak in fall (see Gulf of Lion plate in Fig. 4). In the cold season, this area is the site of deep convection events, mixing water down to 1500-2000 m, occurring systematically when the Mistral blows from the northwest (Anon. 1994). The imagery shows, for the same period, low surface temperatures coupled to the so-called 'blue hole' in the pigment field, off the Gulf of Lion, corresponding to the site of deep overturning. In spring, the same area experiences intense blooming, still discernible well into summer.

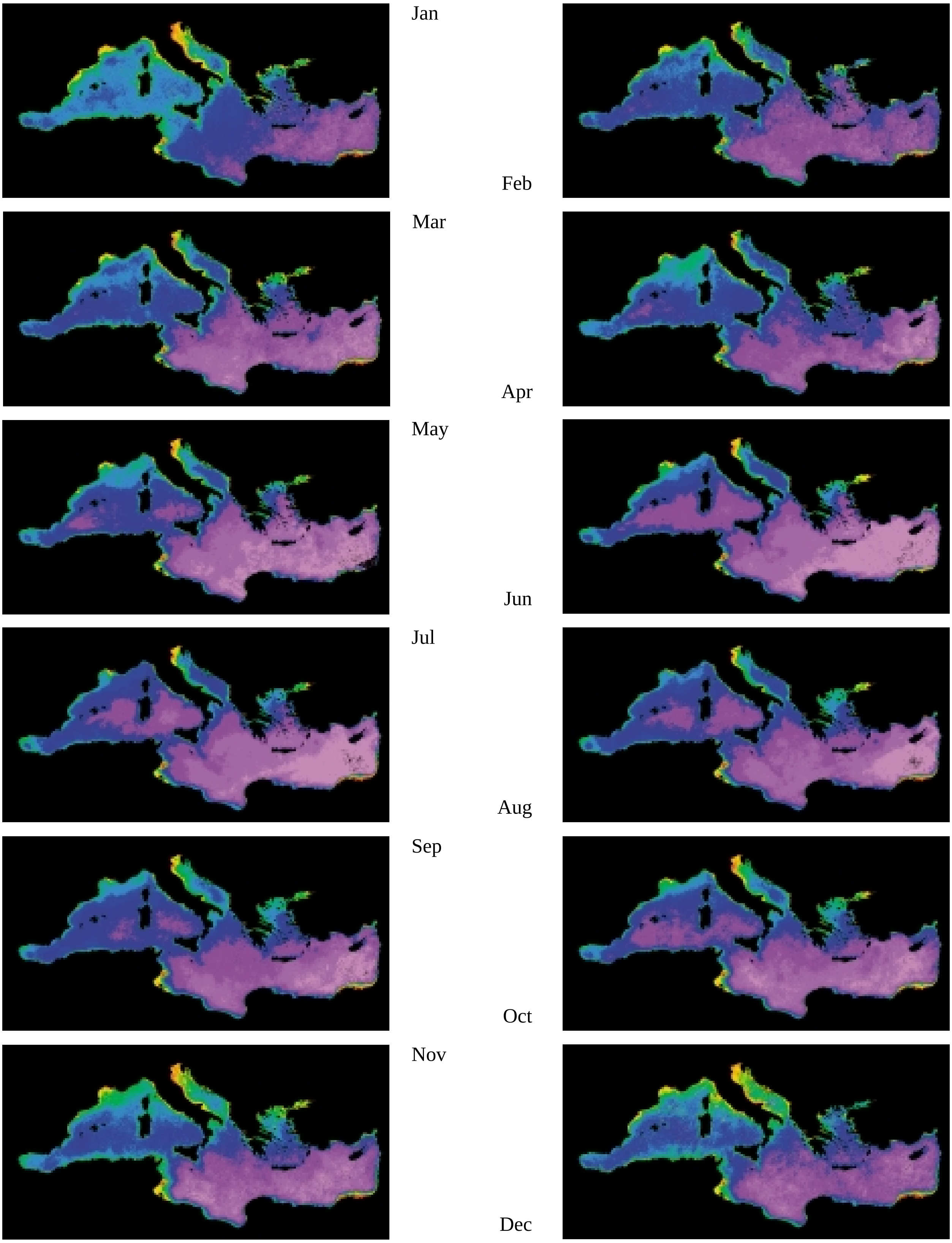

Fig. 3. a. Monthly means of CZCS (1979-1985) chlorophyll-like pigment concentration; the colour coding follows the scheme of Fig. 2a.

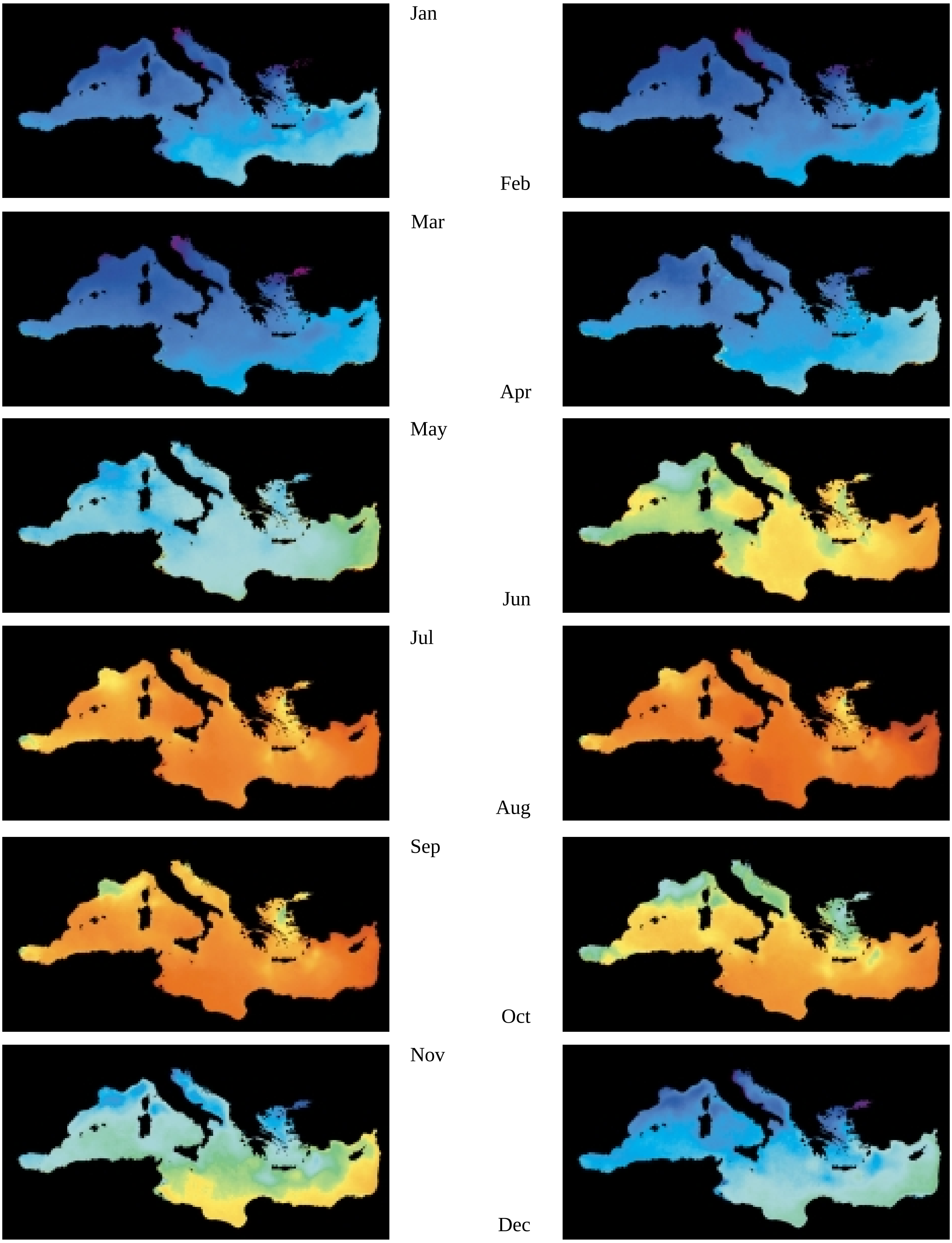

Fig. 3. b. Monthly means of AVHRR (1982-1991) sea surface temperature; the colour coding follows the scheme of Fig. 2b.

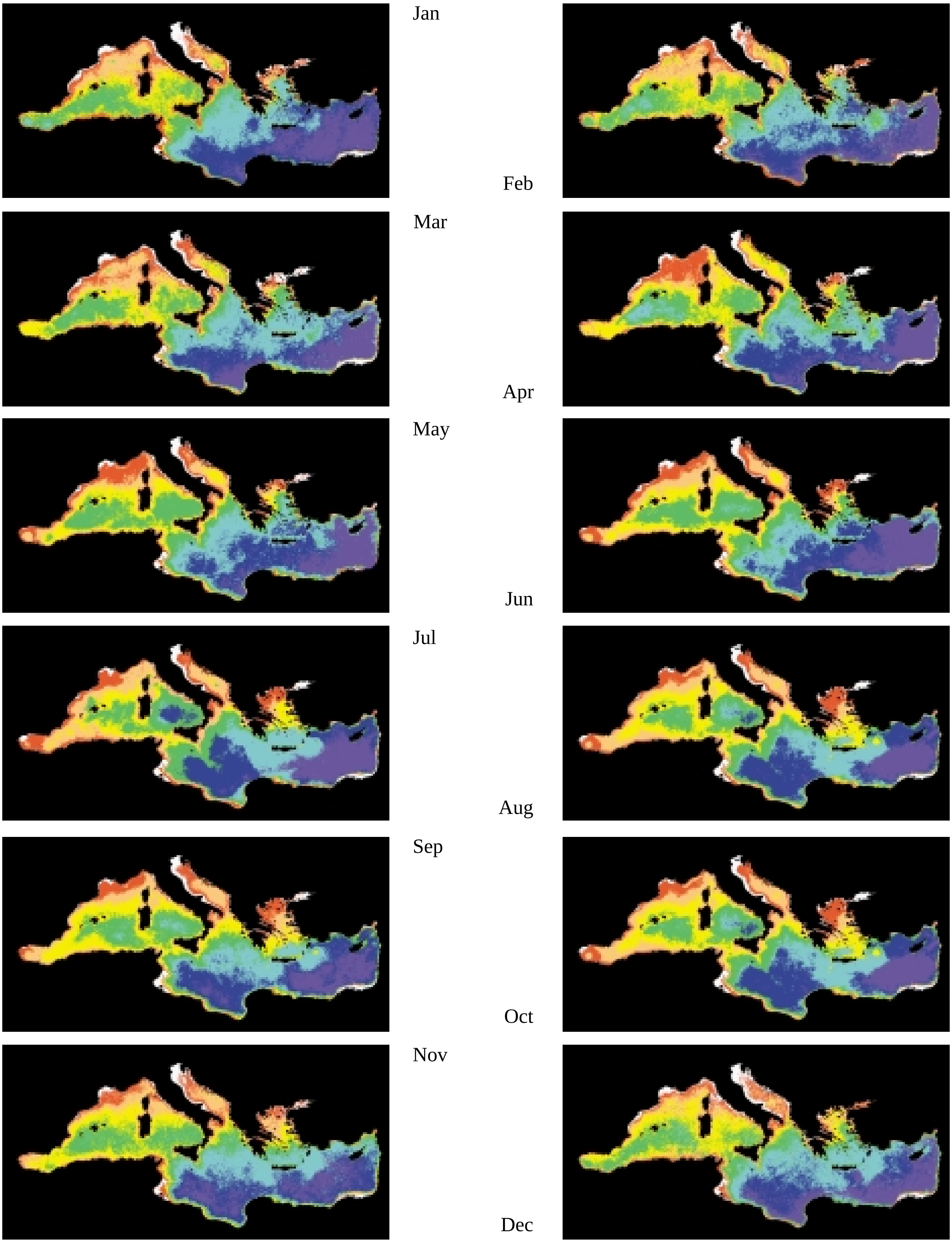

Fig. 3. c. Classified monthly pigment-temperature images; the arbitrary colour coding follows the scheme of Fig. 2c.

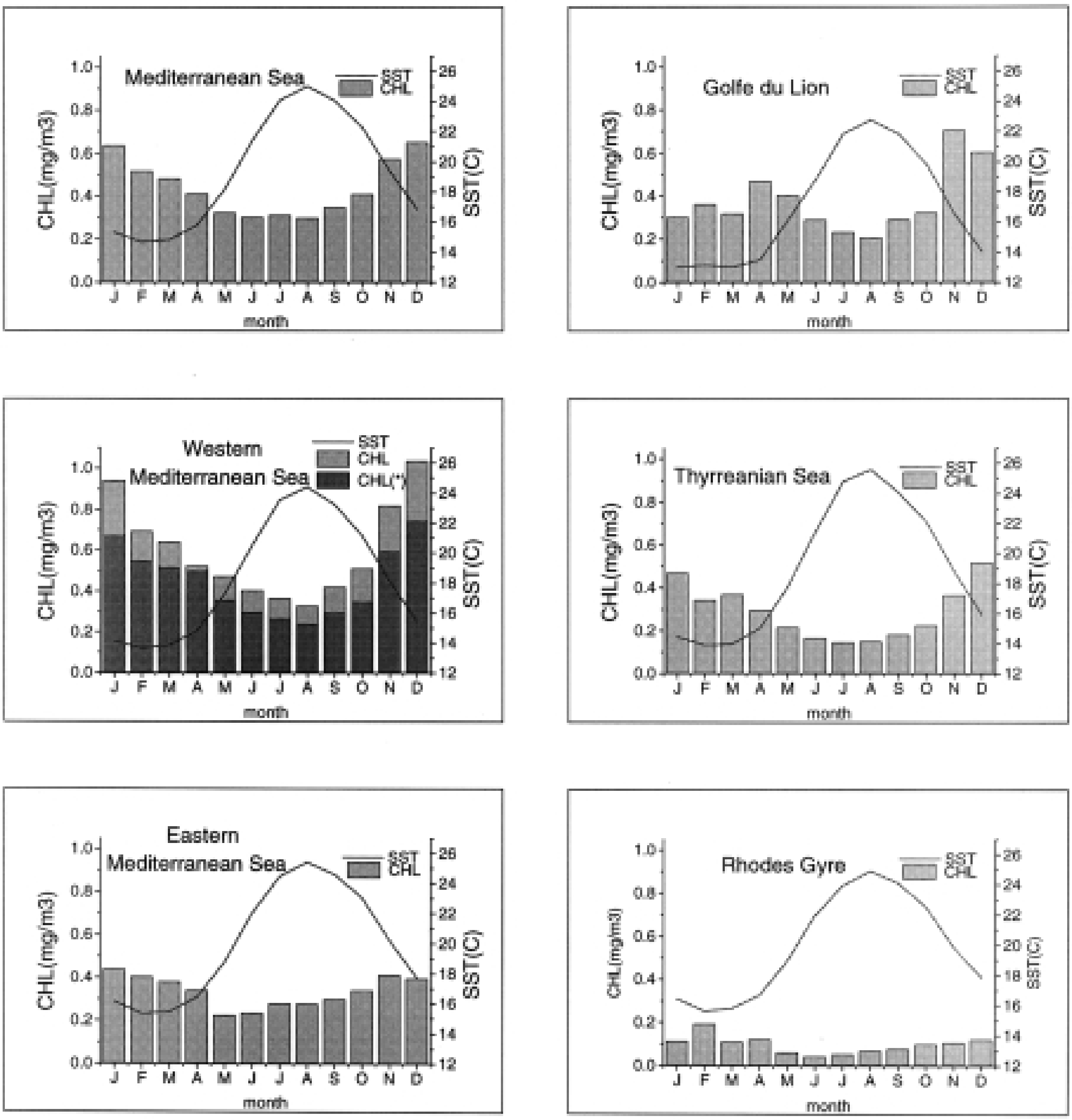

Fig. 4. Seasonal evolution of mean chlorophyll-like pigment concentration (CHL), and mean sea surface temperature (SST), derived from the CZCS (1979-1985) and AVHRR (1982-1991) monthly composites. The means are computed over the entire Mediterranean Sea, the western basin with and (*) without the Adriatic Sea, and the eastern basin (left column figures). Further, the means computed in the central Thyrrenian Sea, the Gulf of Lion, and the Rhodes Gyre are shown (right column figures).

An analogous feature can be observed also in the seasonality of the eastern Mediterranean, where the Rhodes Gyre shows corresponding minimum temperatures and maximum pigments in the period of late winter, early spring (see Rhodes Gyre Plate in Fig. 4). Unfortunately, even though this kind of pattern has been reported before in the literature, no conclusive evidence can be derived from the available images to link the observed trends to the impact of Sahara dust on coccolith blooms, known to produce seasonal variations of surface optical properties in this Mediterranean sub-basin (Azov 1986; Berman et al. 1986).

In the monthly images, a pattern of increasing pigments and decreasing temperatures is seen to develop from the coastal zone towards the basin interior from summer to winter, and then back from winter to summer – in agreement with the 'tropical' behaviour hypothesis. The impact of continental interactions – fluvial and coastal runoff, in particular – and wind-driven upwelling/mixing would then propagate with exchanges between coastal zone and open sea. Therefore, atmospheric forcing (precipitation, resulting in coastal runoff, and wind patterns) would appear to play an important role in establishing the observed space/time distribution of water characteristics. Moreover, in this interpretation, differences in geomorphology and meteorology of the basin margins would have major effect on both water dynamics and biogeochemistry, influencing the entire Mediterranean region, and would be associated with the bio-optical and thermal characteristics of the various sub-basins.

Conclusion

The goal of the work presented here has been to assess the main surface properties of the pigment and temperature fields in the Mediterranean Sea, exploring in particular the apparent impact of continental margins onto the entire basin. This assessment was based on the comparison of long-term means derived from historical time series of remote sensing data, collected by orbital systems (CZCS and AVHRR). The main issues approached concern (1) the role of known patterns of atmospheric forcing (wind, temperature, rainfall) over continental margins, in establishing the observed space/time distribution of water constituents; (2) the role of continental features (bordering orography, hydrology, coastal runoff) in the dynamics of nutrient fluxes and productivity in the basin; and (3) the relationship between the observed basin-wide seasonal patterns and the annual weather cycles of the Mediterranean region.

The major features, detected in the historical data from the 1980s sets, appear to be persistent, and point to specific biogeographical provinces, where a significant relationship seems to exist between optical/thermal indices and the climate of the region. The seasonal patterns derived from the historical data also appear to be real: the basin as a whole experiences a background seasonality, on which other specific sub-basin components are superimposed. The observed space/time patterns of optical and thermal surface properties suggest a correlation with other climatic variables such as wind, rainfall (over catchment basins), runoff, and geographical features such as coastal orography and bathymetry. The fertilization of the Mediterranean basin appears to be due mainly to coastal interactions (even though at least one major fertilization process in the eastern Mediterranean, i.e. the input of Sahara dust carried by southerly winds, could not be assessed in the present data set), with a component due to its thermohaline circulation. Therefore, it is suggested that the biogeochemistry of the system seems to be driven primarily by geographic (morphological) and climatic (meteorological) factors.

As new remote sensing data become available we may be able to clarify these issues and enhance our understanding of the vulnerability of the Mediterranean region to climatic change (possibly through the development of suitable models) and, in the long run, of the possible consequences of changes in the coastal zone on the social problems and marketable resources of the basin (Briand 1992).

Acknowledgements. The present work has been carried out primarily in the framework of OCEAN and CORSA Projects conducted at the Joint Research Centre (JRC) of the European Commission (EC). The authors wish to express their gratitude to the colleagues of the Marine Environment (ME) unit of the Space Applications Institute (SAI), who contributed to the successful development of the work, and in particular to N. Hoepffner for his input concerning the interpretation of CZCS data. Thanks are due to L. Nykjær, responsible scientist for the CORSA Project, and to C. Villacastin, for providing the AVHRR data used in the present work.

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Received 19 January 1999;
Revision received 7 December 1999;
Accepted 7 December 1999.

App. 1. The time series of historical CZCS and AVHRR images used in the present work have been developed and are maintained by the Marine Environment (ME) unit of the Space Applications Institute (SAI), at the Joint Research Centre (JRC) of the European Commission (EC). A World Wide Web (WWW) server has been developed, to increase awareness and promote use of these data sets. The server is available at the address **http://me-www.jrc.it/** and provides immediate access to remote users, *via* INTERNET, to the CZCS and the AVHRR data sets, as well as to subsets, profiles and trends in both image and numerical form.